Independent harmonic cascades for LUX

1. Introduction

This note summarizes initial thoughts on requirements for independent harmonic cascade FEL's in the return straights of each pass of the recirculating linac. The concept is shown schematically for a four-pass configuration in Figure 1. We also investigate a three-pass scheme with a higher energy linac. This report outlines suitable parameters with which to begin a detailed study using FEL simulation codes.

In the harmonic cascade technique a short portion of an electron bunch is modulated and radiates at a harmonic of the modulating signal in an FEL. Successive frequency harmonics are obtained by delaying the electron bunch such that a fresh, unperturbed portion of the bunch is modulated at each stage and then radiates at the shorter wavelength. The scheme is described in more detail in [FAWL]. The EUV and soft x-ray beamlines from these cascades provide independently operable photon sources for common experimental needs such as

- VUV photoemission of valence states: 15-100 eV
- C, N, and O K-edges: 290 eV, 400 eV, 530 eV
- Transition metal L-edges: 600-1000 eV

To ensure complete coverage of the 15 ev – 1200 eV photon energy, each harmonic cascade FEL is seeded by a UV laser tunable over 190-250 nm, and undulators are tunable from second to fifth harmonic of the upstream modulation. Present conventional technology is capable of a few μJ per pulse over this seed laser wavelength range. We extrapolate to an optical seed of 25 μJ in a 10 fs pulse, and 100 μJ in a 100 fs pulse. A peak current of 500 A (1 nC in 2 ps) is to be assumed for the electron bunches, an equal emittance in x and y of 2×10^{-6} m-rad (normalized), and an energy spread of ±200 keV.

An harmonic cascade configuration has previously been described in [FAWL], where a four-stage cascade is studied, with beamlines extracted at each stage. This configuration produces a compact facility with efficient use of the FEL cascade, but limits the independence of each wavelength selection for each beamline. Advantages of the independent harmonic cascades described here are:

- Independent tuning of each FEL beamline; the user has freedom to adjust wavelength without affecting other beamlines
- Avoids necessity of bends between FEL stages to extract beamlines
- Several beamlines may be operated at 10 kHz since a different portion of the same electron bunch may be used to seed FEL's in successive passes
- Multiple beamlines may be incorporated in each straight, increasing the number of user endstations
- Polarization of the photon beam may be achieved by use of a helical undulator in the final radiator only, thereby reducing the number of helical insertion devices in a cascade

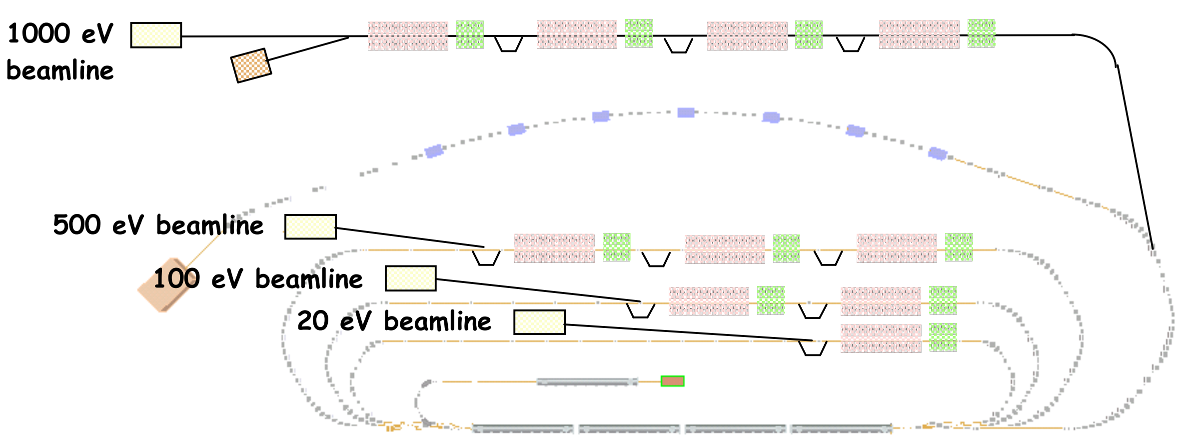

Figure 1 Schematic layout of independent harmonic cascade FEL's in the return straights. The figure is not to scale.

The technique of using a fresh portion of the electron bunch at each stage of the cascade allows the same bunch to be used in each pass. The electron bunch is 3 ps duration, and each stage in the FEL modulation/radiation process uses a 100 fs slice of the bunch. If the timing can be developed such that the electron bunch relative to the laser pulse can be controlled to ±100 fs, then a time window 300 fs duration is needed to ensure that the optical pulse overlaps an unperturbed portion of the electron bunch. There is then the capacity for ten such "windows" overlapping the 3 ps electron bunch – sufficient to seed each of the cascades shown in Figure 1 with the same bunch at 10 kHz. Achieving 100 fs timing jitter may not be practical during commissioning and in early stages of operations, and different bunches may be used for different cascades to overcome this limitation at the cost of reduced pulse repetition rate for some beamlines. The FEL process is easily switched on and off at each cascade by the presence or absence of the seed laser pulse.

Graphs and tables in the following sections indicate possible undulator parameters, for the most part limiting fields to 0.4 T < B_o < 2 T, gaps > 5 mm, and K > 1. A discussion of undulator design parameters is given in the appendix. Final radiator parameters are shown in tables for both planar and helical undulators. The final radiator in each cascade will likely be elliptical or helical to allow production and control of circularly or elliptically polarized photon beams.

Favored undulator configurations are shown in red in the tables. Here we estimate the undulator length requirements by maintaining approximately the same number of periods at each x-ray wavelength as given in a design for a four-stage harmonic cascade reported in [FAWL]. Optimization with FEL simulation codes is required and may lead to slightly different parameters to improve performance.

The optimization of each cascade configuration in terms of FEL output alone would likely lead to each undulator having different design parameters. Reduced development and engineering costs may be expected by having a smaller number of designs. For this reason, undulators have been selected that use common parameters where possible, while expected to maintain reasonable performance in the FEL. Again, this report serves to outline parameters to begin a detailed study with FEL simulation codes.

2. Four-pass configuration

For these estimates we assume a main linac energy of 750 MeV, a total of four passes, and an injected beam energy of 100 MeV.

The four cascades are:

1) 850 MeV, single-stage harmonic generation, producing 83–38 nm or ~ 20 eV
2) 1600 MeV, two-stage harmonic generation, producing 42–7.6 nm or ~ 100 eV
3) 2350 MeV, three-stage harmonic generation, producing 9.3–1.9 nm or ~ 500 eV
4) 3100 MeV four-stage harmonic generation, producing ~ 1 nm or ~ 1000 eV

2.1 850 MeV cascade for 20 eV beamline

The fundamental x-ray wavelength as function of undulator K-value for an 850 MeV beam is shown in Figure 2 [XRAY]. Figure 3 shows the x-ray wavelength as a function of undulator gap [HALB]. Table 1 lists undulator parameters suitable for the 850 MeV harmonic cascade, providing tunability for a beamline in the 20 eV region.

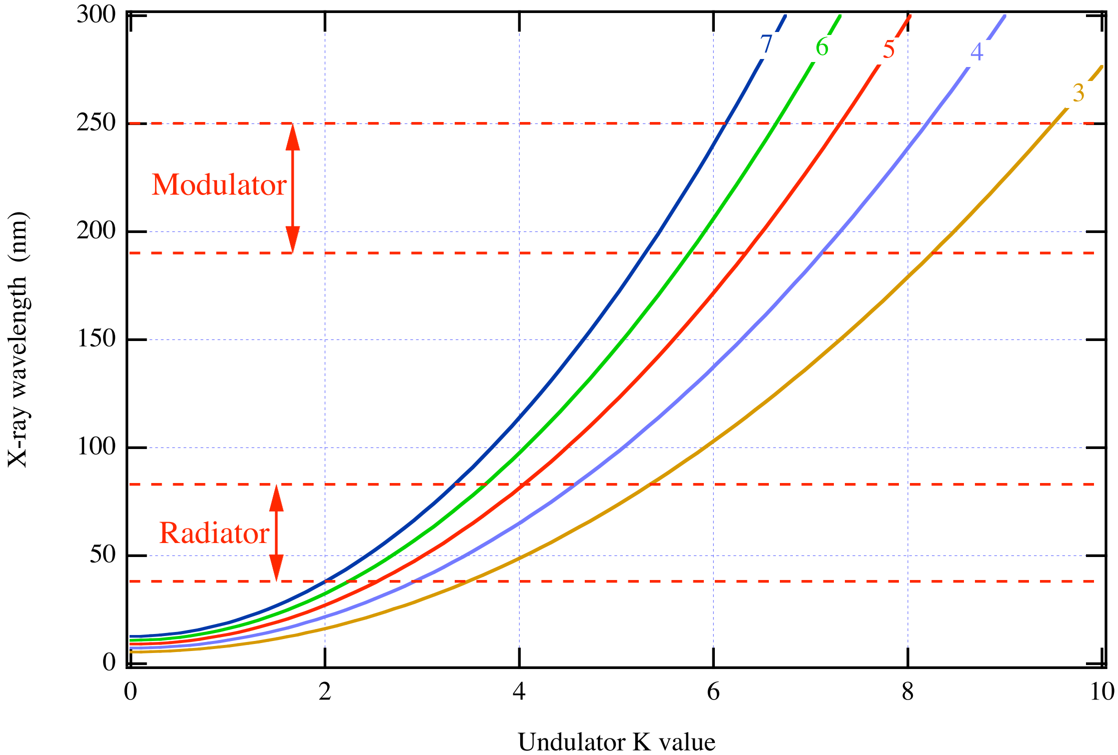

Figure 2. X-ray wavelength of the fundamental as a function of K-value for planar undulators of 3-7 cm period for an 850 MeV beam.

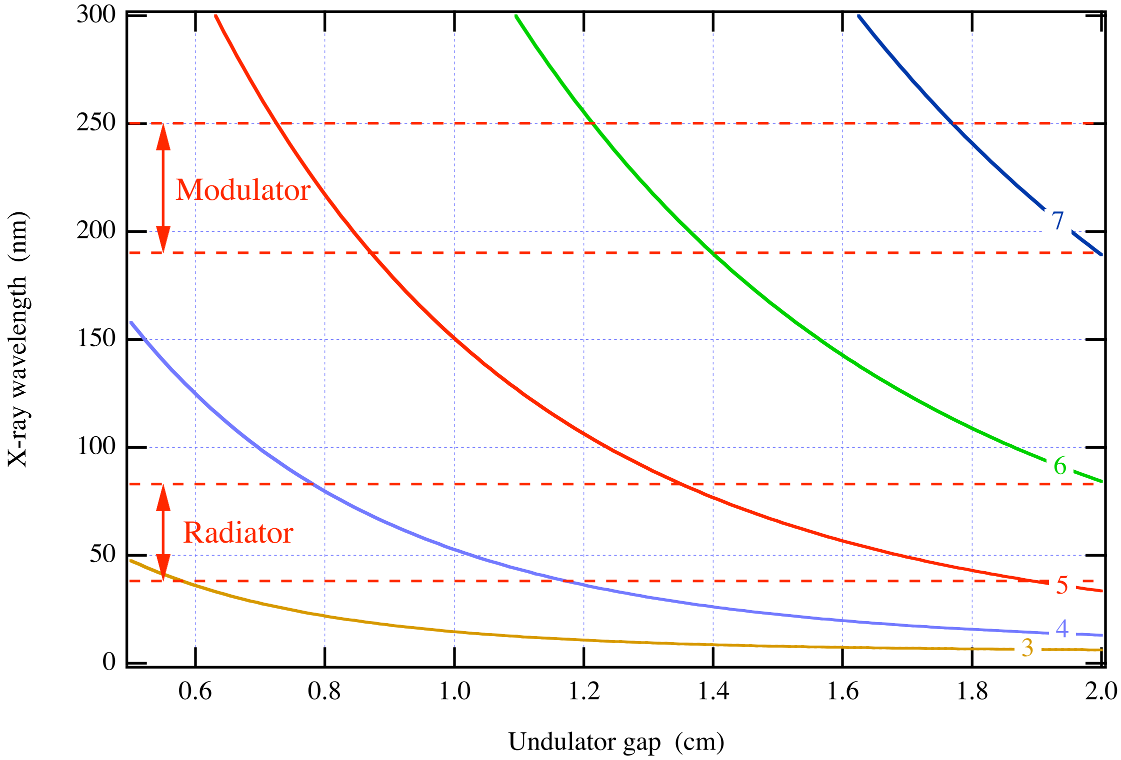

Figure 3. X-ray wavelength of the fundamental as a function of planar undulator gap of 3-7 cm period for an 850 MeV beam.

A 5 cm period modulator has K-value 6.3 at 190 nm, and 7.3 at 250 nm, and peak on-axis field ranging from 1.34 T (K=6.3) to 1.56 T (K=7.3). For the radiator, the fundamental is tuned to 3rd – 5th harmonic of the seed wavelength. A 4 cm period helical undulator is selected for the final radiator rather than a shorter period device since the design may also be used in cascades in higher-energy passes. The modulator length would be approximately 2 m, and the radiator approximately 2 m, but both may be longer when optimized. Depending on detailed layout, several such cascades could be accommodated in the first pass of the machine.

Table 1. 850 MeV harmonic cascade undulator parameters for 20 eV beamline.

	Photon energy (eV)		Photon wavelength (nm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
Modulator	5.0	6.5	250	190	5	7.3	6.3	1.56	1.36	30	2
					6	6.6	5.7	1.19	1.03		2
Radiator	15	33	83	38	4	4.6	2.9	1.23	0.78	53	2
					5	4.1	2.5	0.87	0.54		3
(helical)	15	33	83	38	3	3.8	2.5	1.35	0.87		2
					4	3.2	2.1	0.87	0.55		2

The 100 eV photon range is a little more difficult to reach in the first pass at 850 MeV without short-period, narrow-gap insertion devices. To extend to this photon energy range, a 4 cm planar radiator/modulator pair would be required, and a final helical radiator of approximately 3 cm period.

2.2 1600 MeV cascade for 100 eV beamline

Two stages of harmonic generation are used. Following modulation by the seed laser, a radiating undulator is tuned to the 3rd – 5th harmonic of the seed, and this is followed by a similar modulating undulator. The final radiator is then tuned to 2nd – 5th harmonic of the immediately upstream modulation, producing a tunable beamline spanning the 100 eV region. Table 2 summarizes potential undulator parameters. The overall length of the cascade, assuming 2 m for chicane between radiator and modulator and for focusing quadrupoles would be approximately 20 m. A maximum of two such beamlines could be accommodated in the LUX return straight, although a detailed layout is yet to be produced, including space required for the beamline endsations.

2.3 2350 MeV cascade for 500 eV beamline

Three stages of harmonic generation are used to reach the 500 eV region. Table 3 summarizes results. The overall length of the cascade would be approximately 40 m, and one such cascade would fit in the available space.

Table 2. 1600 MeV harmonic cascade undulator parameters for 100 eV beamline.

	Photon energy (eV)		Photon wavelength (nm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
Modulator	5.0	6.5	250	190	7	11.7	10.2	1.80	1.56	30	2
					8	11.0	9.5	1.47	1.28		2
					9	10.3	9.0	1.23	1.07		3
					10	9.8	8.5	1.05	0.91		3
Radiator & modulator	15	33	83	38	5	8.0	5.3	1.70	1.13	65	3
					6	7.2	4.8	1.29	0.85		4
					7	6.7	4.4	1.02	0.67		5
Radiator	30	163	42	7.6	4	6.2	2.3	1.67	0.62	150	6
					5	5.5	2.0	1.19	0.43		8
					6	5.0	1.7	0.90	0.31		9
(helical)	30	163	42	7.6	3	5.1	2.0	1.83	0.71	150	5
					4	4.4	1.7	1.18	0.44		6
					5	3.9	1.4	0.84	0.30		8

Table 3. 2350 MeV harmonic cascade undulator parameters for 500 eV beamline.

	Photon energy (eV)		Photon wavelength (nm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
Modulator	5.0	6.5	250	190	10	14.5	12.6	1.55	1.35	30	3
					11	13.8	12.0	1.34	1.17		3
					12	13.2	11.5	1.18	1.02		4
Radiator	15	33	83	38	6	10.7	7.2	1.92	1.28	65	4
& modulator					7	9.9	6.6	1.52	1.01		5
					10	8.3	5.5	0.89	0.59		7
Radiator	45	163	28	7.6	4	7.5	3.8	2.02	1.00	138	6
& modulator					5	6.7	3.3	1.44	0.71		7
					6	6.1	3.0	1.09	0.53		8
Radiator	134	816	9	1.5	3	4.9	1.5	1.75	0.54	167	5
					4	4.2	1.1	1.12	0.30		7
					5	3.7	0.8	0.79	0.16		8
(helical)					2	4.3	1.5	2.31	0.80		3
					3	3.5	1.1	1.24	0.38		5
					4	3.0	0.8	0.79	0.21		7

2.4 3100 MeV cascade for 1000 eV beamline

In the final cascade, the nm range is reached by four stages of harmonic generation. Table 4 summarizes results. In this cascade, each stage uses the same harmonics as in previous energy passes, apart from the final radiator which operates on the second to fifth harmonic of the immediately upstream radiator. The operation of the final stage FEL is not expected to be below ~1 nm wavelength due to the emittance of the beam limiting the FEL interaction at shorter wavelengths. The final undulator radiating at ~ 1000 eV has a 1.3 T field with period 2 cm, requiring a small gap for a hybrid design. The situation is eased by being in the final section of the machine thereby accommodating a smaller aperture with less significant concern for wakefield effects deteriorating the beam, and in addition superconducting devices are capable of providing the required field with aperture > 5 mm. The overall length of the cascade would be approximately 60-70 m. The facility layout will be designed to accommodate as many such cascades in parallel as possible.

Table 4. 3100 MeV harmonic cascade undulator parameters for 1000 eV beamline.

	Photon energy (eV)		Photon wavelength (nm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
Modulator	5.0	6.5	250	190	9	20.2	17.6	2.40	2.09	30	3
					10	19.1	16.7	2.05	1.78		3
					11	18.2	15.9	1.78	1.55		3
Radiator & modulator	15	33	83	38	8	12.3	8.2	1.65	1.10	65	5
					9	11.6	7.8	1.38	0.92		6
					10	11.0	7.3	1.18	0.79		7
Radiator & modulator	45	163	28	7.6	5	8.9	4.5	1.91	0.97	138	7
					6	8.1	4.1	1.45	0.73		8
					7	7.5	3.7	1.15	0.57		10
Radiator & modulator	134	816	9.3	1.5	4	5.7	1.9	1.52	0.51	150	6
					5	5.0	1.6	1.08	0.34		8
Radiator	670	1632	1.9	0.8	2	3.4	1.9	1.83	1.01	320	6
					2.5	3.0	1.6	1.28	0.67		8
					3	2.7	1.3	0.95	0.47		10
(helical)					1.5	2.8	1.7	2.03	1.18		5
					2	2.4	1.3	1.29	0.72		6
					2.5	2.1	1.1	0.90	0.48		8

3. Three-pass configuration

For these estimates we assume a main linac energy of 1000 MeV, a total of three passes, and an injected beam energy of 100 MeV.

The four cascades are:

1) 1100 MeV, single-stage harmonic generation, producing 83–38 nm or ~ 20 eV
2) 1100 MeV, two-stage harmonic generation, producing 42–7.6 nm or ~ 100 eV
3) 2100 MeV, three-stage harmonic generation, producing 9.3–1.9 nm or ~ 500 eV
4) 3100 MeV four-stage harmonic generation, producing ~ 1 nm or ~ 1000 eV

3.1 1100 MeV cascade for 20 eV beamline

Table 5 summarizes undulator parameters. The overall length of the cascade would be approximately 4-5 m. Depending on detailed layout, several such cascades could be accommodated in the first pass of the machine in addition to a 100 eV beamline cascade.

3.2 1100 MeV cascade for 100 eV beamline

Table 6 summarizes undulator parameters. The overall length of the cascade would be approximately 17-20 m, and depending on detailed layout, likely one or two such cascades could be accommodated in the first pass of the machine in addition to 20 eV beamline cascades.

3.3 2100 MeV cascade for 500 eV beamline

Table 7 summarizes undulator parameters. The overall length of the cascade would be approximately 40 m, and only one such cascade would fit in the available space.

3.4 3100 MeV cascade for 1000 eV beamline

Table 8 summarizes undulator parameters. Note that the differences with Table 4 arise from choice of insertion devices to minimize number of different designs. The overall length of the cascade would be approximately 60-70 m. The facility layout will be designed to accommodate as many such cascades in parallel as possible.

Table 5. 1100 MeV harmonic cascade undulator parameters for 20 eV beamline.

	Photon energy (eV)		Photon wavelength (nm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
Modulator	5.0	6.5	250	190	5	9.5	8.3	2.04	1.77	30	2
					6	8.7	7.5	1.55	1.34		2
					7	8.0	7.0	1.23	1.06		2
Radiator	15	33	83	38	4	6.1	4.0	1.62	1.06	53	2
					5	5.4	3.5	1.15	0.74		3
(helical)					3	5.0	3.3	1.78	1.17		2
					4	4.3	2.8	1.15	0.75		2

Table 6. 1100 MeV harmonic cascade undulator parameters for 100 V beamline.

	Photon energy (eV)		Photon wavelength (nm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
Modulator	5.0	6.5	250	190	5	9.5	8.3	2.04	1.77	30	2
					6	8.7	7.5	1.55	1.34		2
					7	8.0	7.0	1.23	1.06		2
Radiator	15	33	83	38	4	6.1	4.0	1.62	1.06	65	3
& modulator					5	5.4	3.5	1.15	0.74		3
					6	4.9	3.1	0.87	0.56		4
Radiator	30	163	42	7.6	3	4.9	1.6	1.74	0.59	150	5
					4	4.2	1.2	1.11	0.33		6
					5	3.7	0.9	0.79	0.19		8
(helical)					3	3.4	1.2	1.23	0.41		5
					4	2.9	0.9	0.79	0.23		6
					5	2.6	0.6	0.56	0.14		8

Table 7. 2100 MeV harmonic cascade undulator parameters for 500 eV beamline.

	Photon energy (eV)		Photon wavelength (nm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
Modulator	5.0	6.5	250	190	7	15.5	13.5	2.37	2.06	30	2
					8	14.5	12.6	1.94	1.68		2
					9	13.6	11.9	1.62	1.41		3
					10	12.9	11.2	1.38	1.20		3
Radiator	15	33	83	38	5	10.5	7.0	2.25	1.50	65	3
& modulator					6	9.6	6.4	1.71	1.14		4
					7	8.9	5.9	1.35	0.90		5
Radiator	45	163	28	7.6	4	6.7	3.3	1.79	0.88	138	6
& modulator					5	6.0	2.9	1.28	0.62		7
					6	5.4	2.6	0.97	0.46		8
Radiator	134	816	9	1.5	3	4.3	1.2	1.55	0.43	167	5
					4	3.7	0.8	0.99	0.20		7
(helical)					2.5	3.4	1.0	1.45	0.44		4
					3	3.1	0.8	1.10	0.30		5
					4	2.6	0.5	0.70	0.14		7

Table 8. 3100 MeV harmonic cascade undulator parameters for 1000 eV beamline.

	Photon energy (eV)		Photon wavelength (nm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
Modulator	5.0	6.5	250	190	9	20.2	17.6	2.40	2.09	30	3
					10	19.1	16.7	2.05	1.78		3
					11	18.2	15.9	1.78	1.55		3
Radiator & modulator	15	33	83	38	8	12.3	8.2	1.65	1.10	65	5
					9	11.6	7.8	1.38	0.92		6
					10	11.0	7.3	1.18	0.79		7
Radiator & modulator	45	163	28	7.6	4	10.0	5.1	2.68	1.36	138	6
					5	8.9	4.5	1.91	0.97		7
					6	8.1	4.1	1.45	0.73		8
Radiator & modulator	134	816	9.3	1.5	3	6.6	2.3	2.35	0.83	150	5
					4	5.7	1.9	1.52	0.51		6
Radiator	670	1632	1.9	0.8	2	3.4	1.9	1.83	1.01	320	6
					2.5	3.0	1.6	1.28	0.67		8
					3	2.7	1.3	0.95	0.47		10
(helical)					1.5	2.8	1.7	2.03	1.18		5
					2	2.4	1.3	1.29	0.72		6
					2.5	2.1	1.1	0.90	0.48		8

Table 9. 100 MeV and 300 MeV undulator parameters for THz beamline.

Beam energy (MeV)	Photon energy (meV)		Photon wavelength (μm)		λ_u (cm)	K		B_0 (T)		# periods	Length (m)
100	1.2	2.5	1000	500	20	27.6	19.5	1.48	1.04	10	2.0
					25	24.7	17.4	1.06	0.75		2.5
					30	22.6	15.9	0.80	0.57		3.0
300	1.2	2.5	1000	500	35	62.7	44.4	1.92	1.36	10	3.5
					40	58.7	41.5	1.57	1.11		4.0
					50	52.5	37.1	1.12	0.79		5.0

4. THz beamline from the injector linac

Longer wavelength radiation is most easily produced with lower energy electron beams, and the injector linac may be an excellent source of infra-red and THz radiation. Table 9 shows some potential wavelength ranges for 100 MeV and 300 MeV injector linac energies, and the associated undulator parameters.

5. Comments and conclusions

This note shows that undulator parameters for independent harmonic cascades in LUX are within the range of standard designs for the most part, and current state-of-the-art for the shortest period devices radiating at 1 nm. Optimization by use of FEL simulation codes is required to develop more robust design parameters.

For the four-pass machine configuration, planar undulators of 10 cm, 4 cm, and 5 cm period provide the modulating stages before a final 4 cm or 2 cm period helical undulator radiates into the beamline.

For the three-pass machine configuration, planar undulators of 10 cm, 6 cm and 4 cm period provide the modulating stages before a final 4 cm, 3 cm, or 2 cm period helical undulator radiates into the beamline.

With the flexibility of the recirculating linac configuration, the bunch longitudinal phase space may be manipulated at each pass. In particular, following the final pass through the linac, the bunch may be compressed in the arc leading to the 1 keV harmonic cascade, thereby increasing peak current with possible gains in FEL performance.

Future developments of laser-induced high-harmonic generation (HHG) in gases may lead to reproducible and controllable pulses suitable to seed the FEL process. If successful, this technology may be applied to seed at significantly shorter wavelengths than the baseline UV region, with the potential to eliminating the need for at least the first stage of modulation at approximately 200 nm.

References

[XRAY] X-ray data booklet, LBNL/PUB-490. See section 2.1 “Characteristics of synchrotron radiation” by K-J Kim.

[FAWL] W. Fawley, W.A. Barletta, J. Corlett, A. Zholents, “Simulation Studies of an XUV/Soft X-Ray Harmonic-Cascade FEL for the Proposed LBNL Recirculating Linac”, Proc. 2003 Particle Accelerator Conference, LBNL-52596.

[HALB] K. Halbach, “Permanent Magnet Undulators”, J. Physique, C1, Suppl.2, **44** (February 1983).

Appendix - Undulator design parameters

The fundamental wavelength $\lambda_{x\text{-}ray}$ for a planar undulator is given in nm by [XRAY]:

$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right) = \frac{1.3056\ \lambda_{undulator}\ [cm]}{E^2\ [GeV]}\left(1+\frac{K^2}{2}\right)$$

and for a helical undulator by:

$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1+K^2\right) = \frac{1.3056\ \lambda_{undulator}\ [cm]}{E^2\ [GeV]}\left(1+K^2\right)$$

where the undulator parameter K is given by:

$$K = \beta\gamma\theta = \frac{e\ \lambda_{undulator}\ B_0}{2\pi\ m\ c} = 0.934\ \lambda_{undulator}\ [cm]\ B_0\ [T]$$

where β is the velocity relative to c, γ is the Lorentz factor, θ is the maximum deflection angle of the beam, $\lambda_{undulator}$ is the undulator period, E is the beam energy, B_0 is the peak magnetic field in the undulator. The difference in expressions between planar and helical undulators reflects the constant angle as viewed from the axis in the helical case and an rms angle in the planar case due a sinusoidal oscillation.

For a planar hybrid undulator with rare-earth cobalt magnetic material and vanadium permendur poles, the following expression describes the peak magnetic field as a function of period and gap for $g < \lambda_{undulator}$ [HALB]:

$$B_o\left[T\right] = 3.33\exp\left[-\frac{g}{\lambda_{undulator}}\left(5.47 - 1.8\frac{g}{\lambda_{undulator}}\right)\right]$$

Figure A1 shows the magnetic field as a function of gap for a range of undulator periods. A practical limit on the pole gap is approximately 5 mm, and a realistic peak field of 0.4-2.0 T. Figure A2 shows the K-value as a function of undulator gap for a range of undulator periods, based on the above model, with limitations of a 5 mm gap and 2 T peak field also identified. For undulator periods less than approximately 5 cm, achieving useful magnetic fields is challenging for hybrid designs. Superconducting technology may be a superior choice for such requirements. Figures A3-A10 show parameters for planar undulators relevant to the designs in this note.

The final radiator in each cascade will allow production and control of circularly polarized photon beams. Permanent magnet designs use split magnet blocks, which may be laterally displaced to provide variable elliptical polarization. Superconducting helical windings allow circular polarization switchable between L, R orientation.

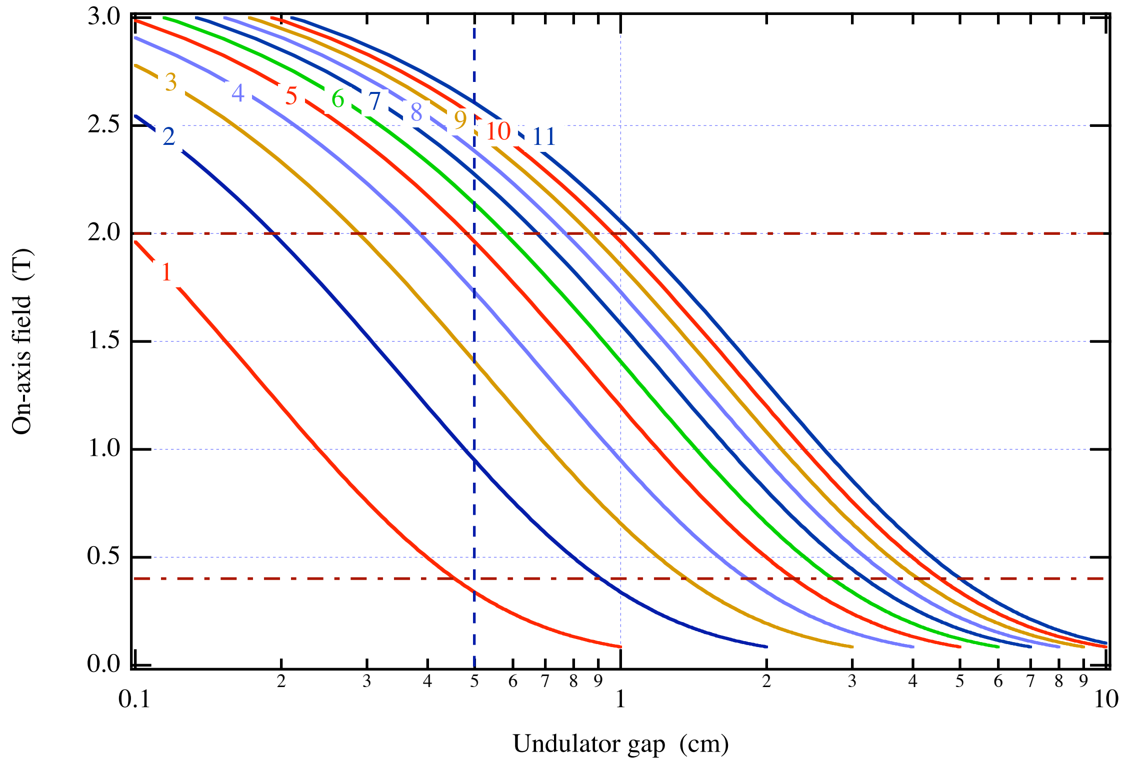

Figure A1. Peak field for planar undulators of 1-11 cm period as a function of gap [HALB]. A pole-gap of 5 mm, and peak fields of 0.4 T and 2 T are indicated.

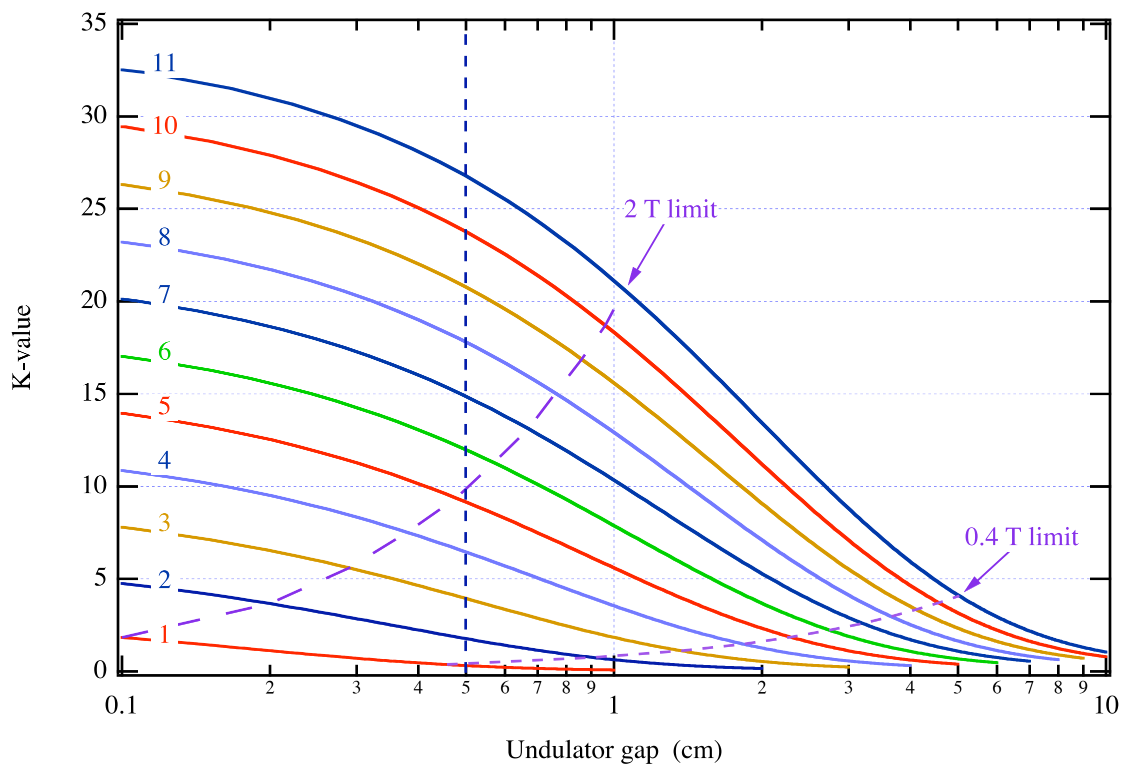

Figure A2. K-value for planar undulators of 1-11 cm period as a function of gap from [HALB]. The vertical dashed line indicates a pole-gap of 5 mm. The curved dashed lines indicate peak field limits of 0.4 T and 2 T.

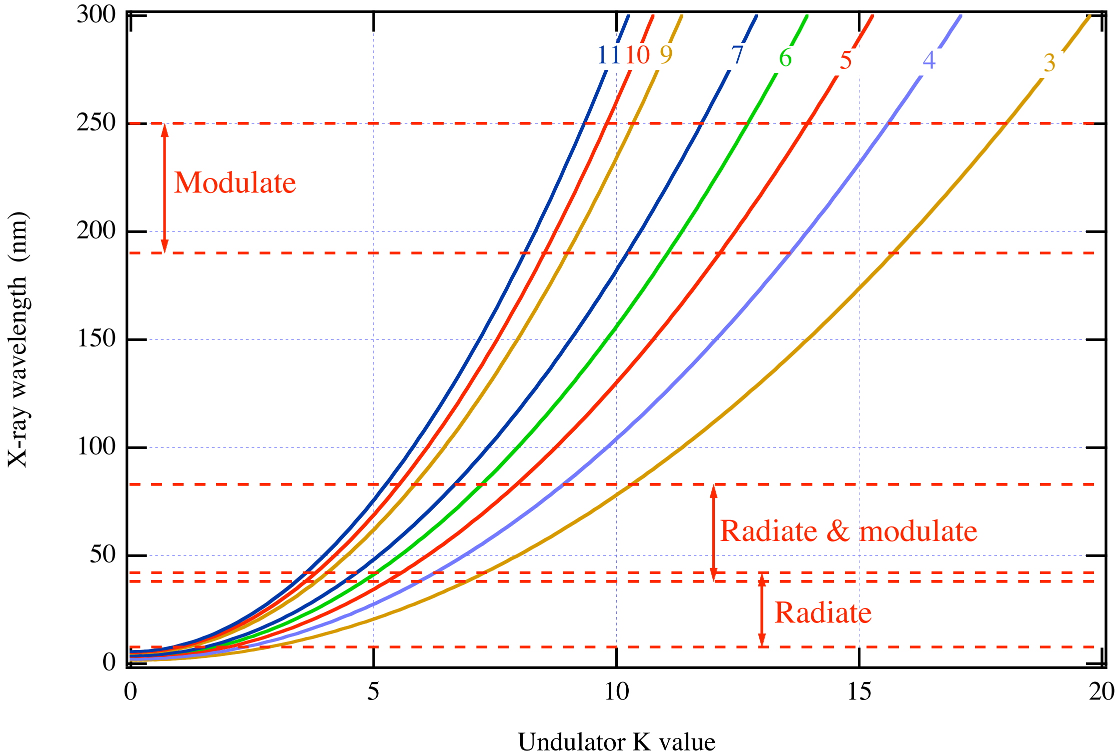

Figure A3. X-ray wavelength of the fundamental as a function of K-value for a range of planar undulator periods and for a 1600 MeV beam. Two stages of harmonic generation are used, modulating and radiating wavelength bands are indicated.

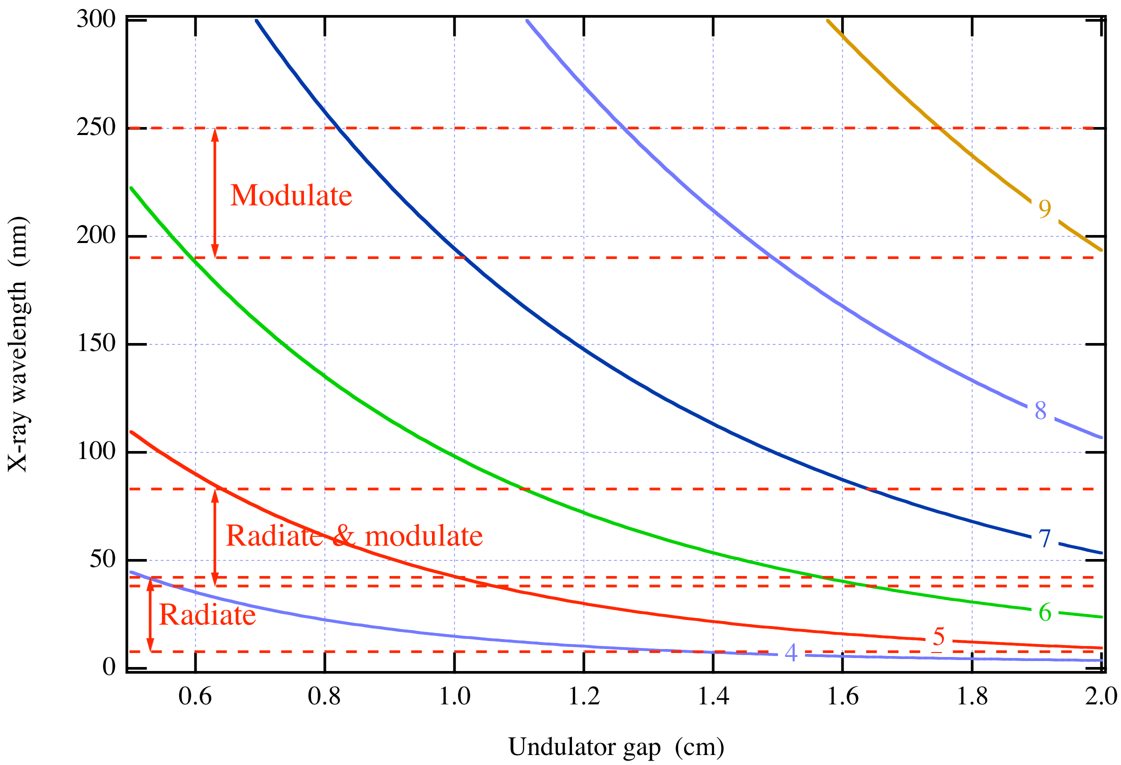

Figure A4. X-ray wavelength of the fundamental as a function of planar undulator gap of 4-9 cm period for a 1600 MeV beam.

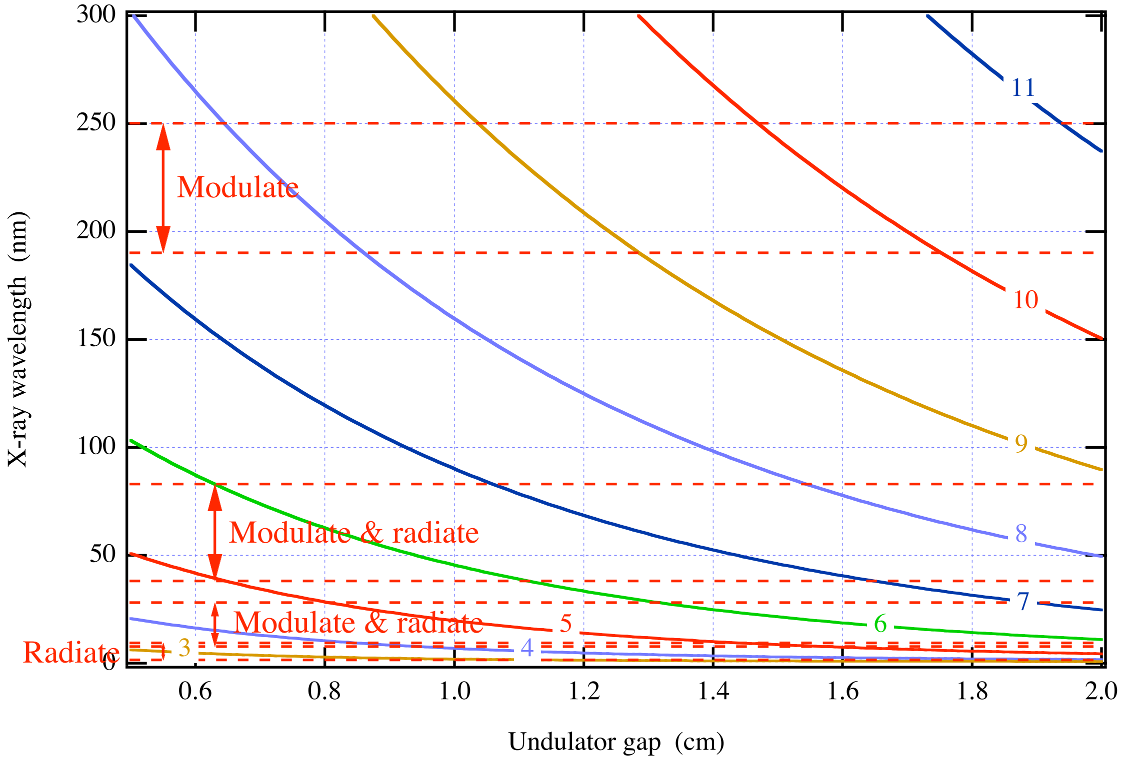

Figure A5. X-ray wavelength of the fundamental as a function of planar undulator gap of 3-11 cm period for a 2350 MeV beam.

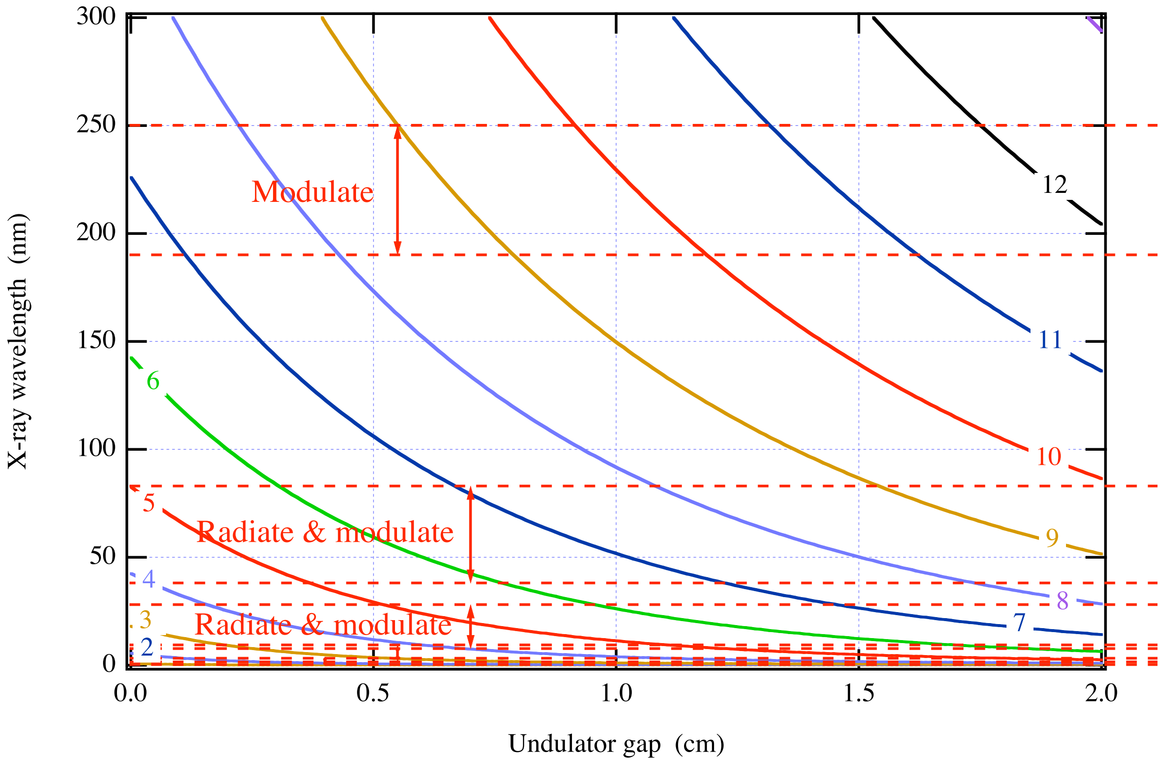

Figure A6. X-ray wavelength of the fundamental as a function of planar undulator gap of 3-12 cm period for a 3100 MeV beam.

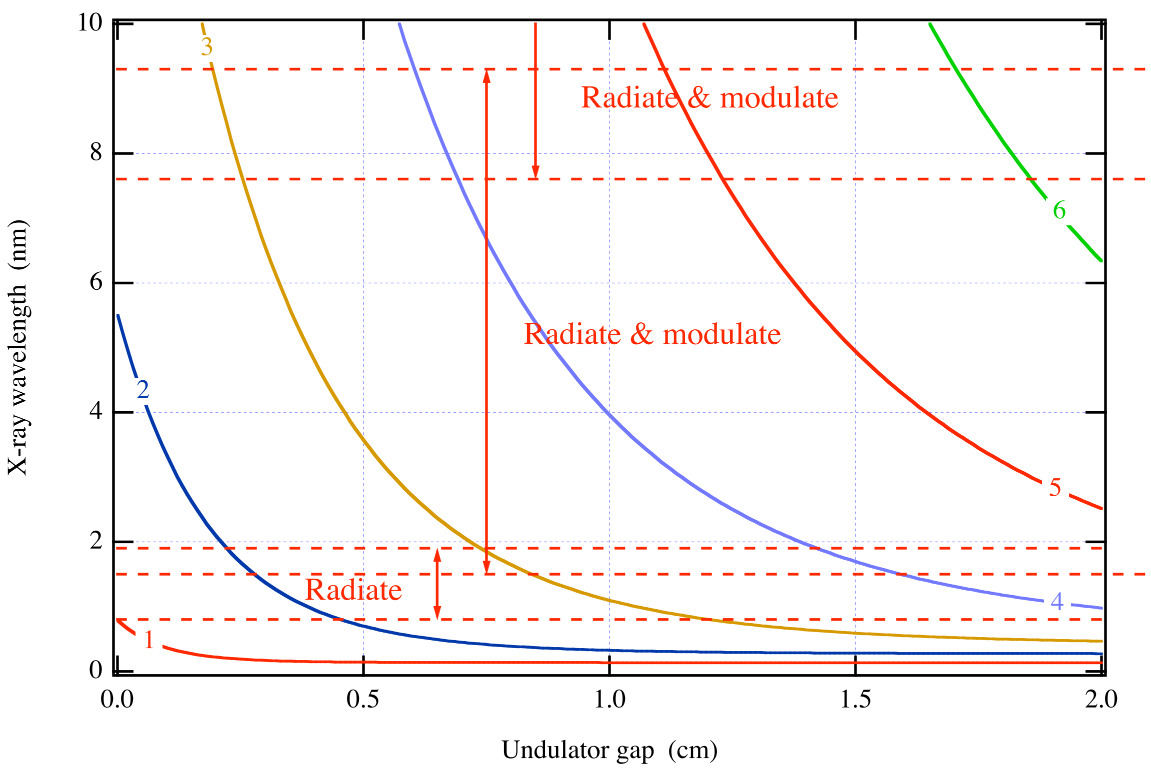

Figure A7. X-ray wavelength of the fundamental as a function of planar undulator gap of 3-6 cm period for a 3100 MeV beam, for the final short-wavelength stages.

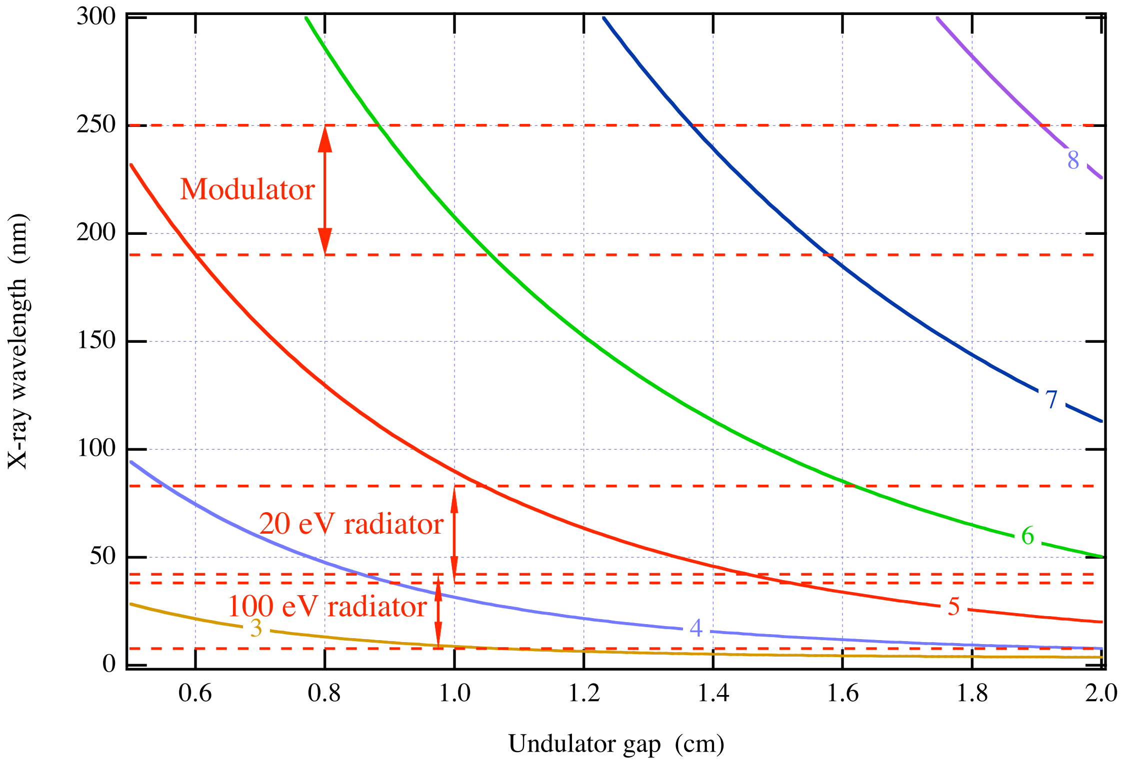

Figure A8. X-ray wavelength of the fundamental as a function of planar undulator gap of 3-8 cm period for an 1100 MeV beam. Wavelength of radiators for the 20 eV and 100 eV beamlines are indicated.

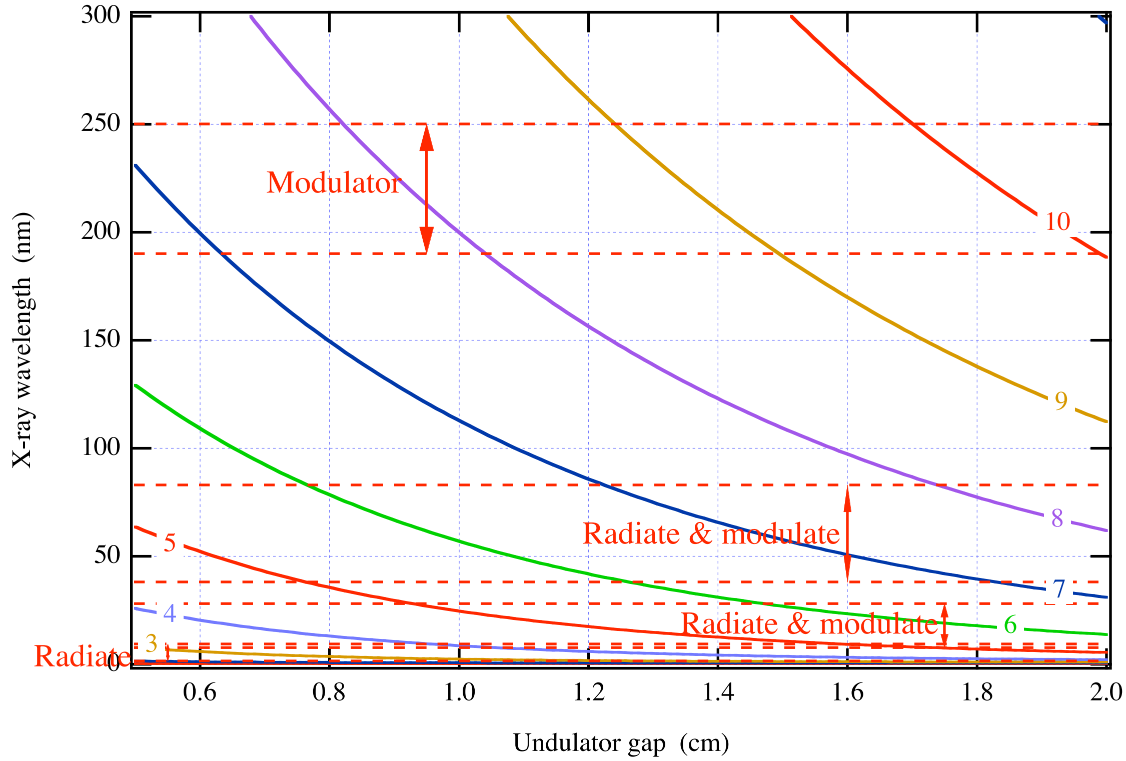

Figure A9. X-ray wavelength of the fundamental as a function of planar undulator gap of 3-10 cm period for a 2100 MeV beam.

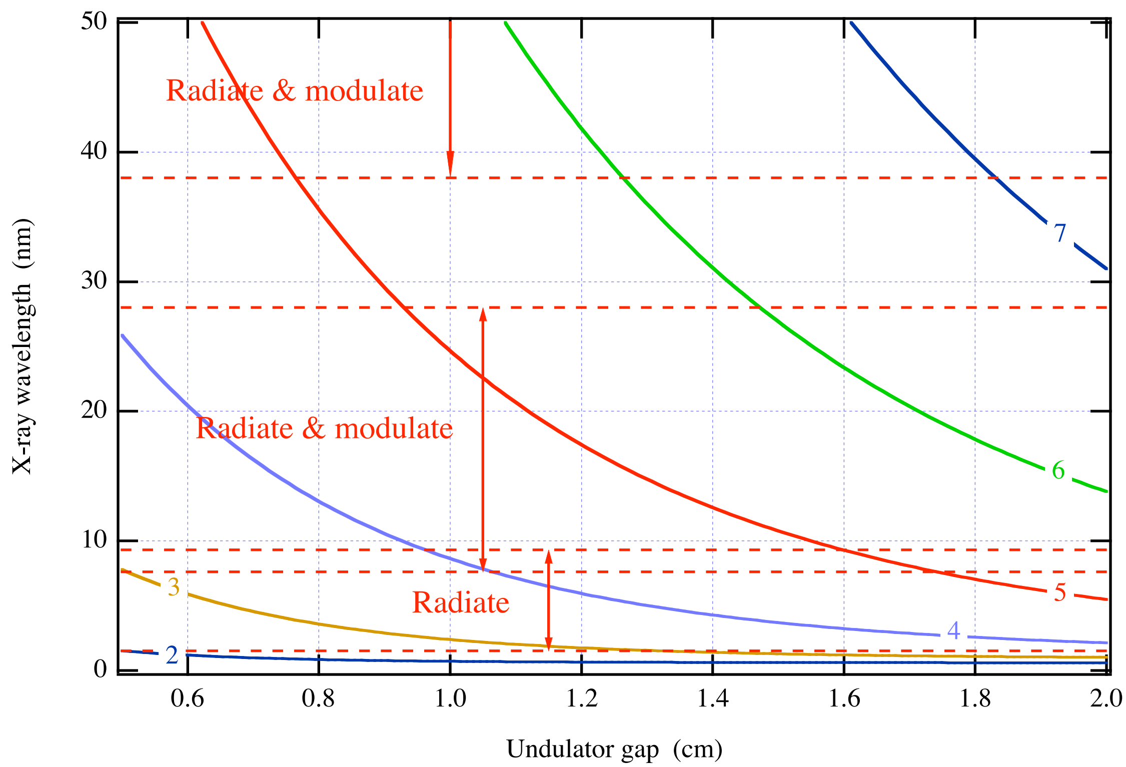

Figure A10. X-ray wavelength of the fundamental as a function of planar undulator gap of 2-7 cm period for a 2100 MeV beam.